Defence Science Journal, Vol. 54, No. 3, July 2004, pp. 271-276

Design of a Six-link Mechanism for a Micro Air Vehicle

S. Mukherjee and S. Sanghi
Indian Institute of Technology Delhi, New Delhi -110 016

ABSTRACT

Micro air vehicle (MAV) is a small flight vehicle that uses lift-generating mechanism different from the mechanism used for a larger aircraft. The MAV may require configurations that are more unusual and approaches, ranging from low aspect ratio fixed wings to rotary wings, or even flapping wings. One of the most efficient lift-generating mechanism in small geometries is observed in the one species of insects *Encarsia formosa*, as reported by Weis Fogh. This is achieved by generating lift prior to setting up of net circulation. In this paper, the design of a flapping mechanism used to realise the Weis Fogh mechanism of lift generation is described. A single-drive design using concepts of motion synthesis by kinematic inversion technique, followed by dynamic analysis, is presented. This simplification opens the way for future miniaturisation of these devices at economic costs.

Keywords: Micro air vehicle, computer-aided design, flapping-wing mechanism, MAV, lift-generating mechanism, Weis Fogh mechanism, kinematic inversion technique, kinematics

1. INTRODUCTION

The definition employed by Defense Advanced Research Projects Agency (DARPA), limits micro air vehicle (MAV) to a size less than 38.10 cm length, width or height[1]. These machines whose mobility can deploy a useful micro payload to a remote or otherwise hazardous location, where it may perform a variety of missions, including reconnaissance and surveillance, targeting, tagging, and biochemical sensing have tremendous potential in defence sector. The MAVs may require configurations that are more unusual and approaches ranging from low aspect ratio fixed wings to rotary wings, or even more radical notions like flapping wings. Many of the mathematical relationships normally used in conventional aircraft design do not apply to the flight of such small devices at very low speeds. Innovative technical solutions are found for aerodynamics and control, propulsion and power, and navigation and communication.

Throughout nature's creation, the life forms that are capable of initiating lift in flight do so through the flapping of wings. Nowhere one observes fixed wings, jets, or propellers for sustained flight in a living creature, existing or extinct. There are no records on the attempts made by the extinct creatures to fly by alternate means. Perhaps, wing flapping is a universal means of sustained biological flight propulsion because the scale may be a factor in the advantage of flapping wing beating over fixed wing. Today's largest flying creatures are the andean condors, which weigh a maximum of up to 15 kg.

The size constraints placed on this design, provides motivation for a flapping mechanism. For the smaller vehicle, a fixed-wing solution is less reasonable

Re-revised 29 April 2004

because fixed-wing vehicles rely on the lift generated by airflow from the vehicle moving through air to support its weight. This lift is directly proportional to wing area and square of the velocity of airflow over the wing. Thus, smaller the linear dimension of the vehicle (the area of the wing decreases as square of the linear dimension), the less lift it can supply. One solution to counter this effect is to increase the velocity of the vehicle. But one can't increase the velocity in situations, such as indoor missions where a MAV makes the most sense. Another advantage of flapping mechanism is that it can hover in the air like insects. Only helicopters presently achieve hovering, but micro helicopters are not feasible because of the mechanical problems of balancing these with tail and gyroscope, etc.

A flapping-wing design can rely on lift generated in two ways: (i) by airflow created by the vehicle speed and (ii) the wing flapping to support the weight of the vehicle. Therefore, if the scale is reduced, the frequency of the beating can be increased without affecting the minimum velocity of the vehicle. This design is not affected by scale changes. The size of an air vehicle could thus be reduced to a size of millimeters, as observed in nature.

Another advantage of flapping-wing mechanism relates to the minimum speed of the vehicle and ability to perform short takeoffs and landings. Provided with enough power, a vehicle with flapping-wing mechanism could actually takeoff and land vertically. As described above, the fixed-wing mechanism is very limited at slow speeds, thus requiring significant distances to increase its speed before attaining flight speeds.

The lift is generated in the flapping wings mainly by shedding of vortices. Initially, as the two wings starts motion, from the clap position at the back, according to Kelvin's circulation theorem, the net circulation around the insect body is zero. Then, as the insect beats its wings back and forth, high lift coefficient is builtup due to vorticity shedding from the trailing edge to generate necessary circulation around the wings.

In ordinary insects, this buildup of high lift coefficient is delayed, because it takes some time after flapping is initiated for the insect to attain the required velocity of wing beating and the circulation around the wing to be developed. Hence to counter the delay, one species of insects, *Encarsia formosa*, precedes each beat with a special movement, which causes the necessary circulation to occur immediately and avoid any delay in builtup of maximum lift[2]. This model, named after the discoverer, Weis Fogh, consists of a pure rotation, followed by a translation and a rotation of the wings.

Conventionally, implementing such complicated motion involves coordination of multiple axis using feedback control. In this paper, the design of a mechanism that implements the motions using a single, constant-speed drive, has been discussed. This simplification opens up the way for future miniaturisation of these devices at economical costs.

2. WEIS FOGH'S 2-D MODEL

For two-dimensional inviscid flow[3], the doctrines of Helmholtz, Stokes, and Kelvin state that a body starting to move in a fluid at rest, retains zero circulation of fluid around it. This retards the generation of lift on the body (or of any force except those associated with virtual mass effect). The doctrines however, do not rule out the possibility that when the body breaks into two pieces, there may be equal and opposite circulation around these, each suitable for generating the lift required, in pieces, in subsequent motions. This possibility is exploited in the Weis Fogh's model.

The model is based on the sequence of motions of the wings of an insect, *Encarisa formosa.* Figure 1 illustrates the wings movements which constitute the Weis Fogh mechanism. The lines represent the two wings in a mid-span vertical plane. Figure 2 gives a full view of the insect body along with the wings. At a certain instant in the wing flapping cycle, the insect performs a clap, ie, both the wings are clapped together [Figs 1(a) and (b)]. The two wings then start to

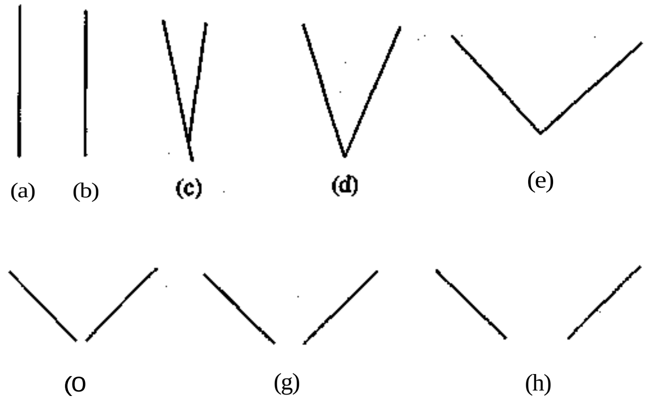

Figure 1. Sequence of motions of the wings of *Encarsia formosa*, as shown in section by a mid-span vertical plane on the dorsal side of the insect's erect body. In positions (a) and (b), the wings are at rest momentarily, after the clap; positions (b)-(f) exhibit the fling motion; the wings break apart at (f) and in (f), (g), and (h), exhibit normal flight movement, moving away from each other.

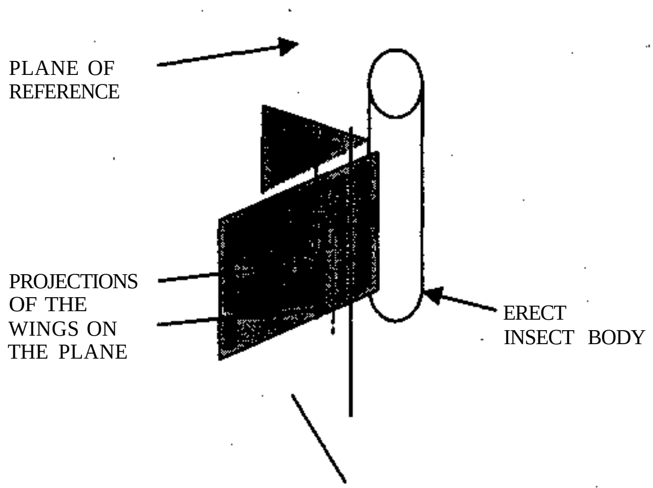

Figure 2. Projection of wings on the plane of reference for Fig. 1.

fling open but are still connected to each other at the bottom so that these effectively form a single body [Figs l(c) to (e)]. Then the wings break apart and are completely separated [Figs 1(f) and (g)]. When the wings break apart, the circulation around each wing is in the opposite directions to generate enough lift at once in the subsequent horizontal motions.

The motion of the wings described above is not one of pure rotation, or pure translation. To generate this class of motion accurately, multiple drives with feedback position control on each axis are required. In this paper, a design that uses a single, fixed-speed drive to achieve the coordinated motion has been proposed.

3. DESIGNING THE FOUR-BAR MECHANISM

3.1 Design Steps

To design the mechanism, the positions of the wings that are required as per the Weis Fogh model, are given in the Figs l(a), l(e) and l(h). These positions are the basis for designing the mechanism. A four-bar mechanism has been designed for the three positions by synthesis using kinematic inversion method as well as drawing functions of AutoCAD 14 to iterate several times to arrive at a feasible solution.

This mechanism is driven by an electric motor, and the wing (output) is in the form of an extension attached to coupler AB, shown in the Fig. 3. The problem for designing the linkage mechanism is identified in a form suitable for classical kinematics synthesis, a motion-generation problem.

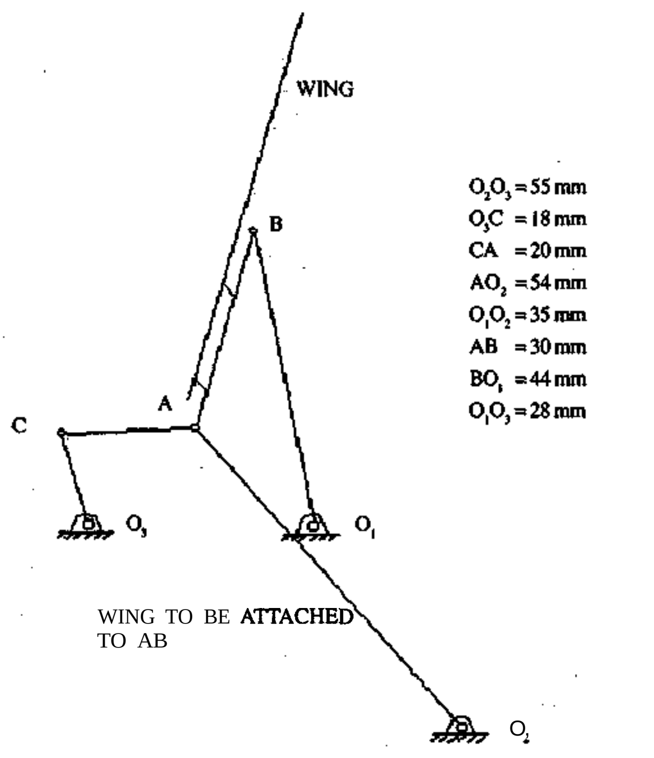

Figure 3. Mechanism designed for generating lift in a micro air vehicle.

The guidance mechanism is a double rocker. To power this, Weis Fogh mechanism using a continuously driven motor, a crank rocker arrangement (O_3CAO_2) has been designed, as shown in the Fig. 3. In this mechanism (Fig. 3), O_3CAO_2 represents the driving crank rocker arrangement, with O_3C as the crank and O_2A the rocker. O_1BAO_2 represents the rocker-rocker pair and the coupler BA has the wing attached to it.

The procedure for developing the mechanism is as follows:

Step 1. First the flapping mechanism, O_1BAO_2 is designed. For the known positions of the wing, assume positions of fixed pivots O_1 and O_2. Subsequently, if a good solution is not obtained, iteration with alternate locations of fixed pivots are needed.

Step 2. Inverting about the extended coupler (wing), the points A and B on link coupler are determined[4]. The links O_1A and O_2B are the driver and the follower of classical four-link mechanisms, respectively.

Step 3. The criterion for a feasible solution is that the links should be in the range 1 cm to 4 cm, for ease of manufacture and miniaturisation. Hence, if the criterion is not satisfied, then *Steps* 1 and 2 are repeated until this criterion is satisfied for all the links.

Step 4. Next the driving mechanism, O_3CAO_2 is designed. In this case, the position of link O_2 is known from the design of flapping mechanism. It is also known that the link O_3C is a crank. A position for O_3 is first chosen on the bisector of the angle formed by the two extreme positions of link O_2.

Step 5. Iterate for some lengths of O_3C, and different positions of O_3. A good design, satisfying the conditions in *Step* 3, was obtained after six iterations.

3.2 Dynamic Analysis

The dynamics and the resultant loads were analysed. The linkages were assumed to be of steel (width 5 mm and thickness 1 mm). The maximum acceleration occured at position of about 120° of link O_1B. This corresponds to position of wing given in Fig. 4(e) and the second reference position of the wing in the design. Hence, a combined static and inertia force analysis[4] of the flapping mechanism at this position is done. The assumptions are as follows:

Assumption 1. The link O_2A is moving with average angular velocity of 100 Hz, and zero angular acceleration.

Assumption 2. The driving mechanism O_3CAO_2 has not included this analysis.

This analysis is used to compute the forces on the pin joints and the links. From the analysis, the maximum force is on joint O_2 and is of magnitude 31.38 N. When the mechanism is oscillating, there are unbalanced forces acting on it. A further detailed force analysis would have helped in balancing the unbalanced forces of this mechanism. In a flying mechanism, imbalances are damped due to viscous interactions in the low Reynolds number regime. All the horizontal forces will be cancelled by oppositely working mechanisms for the two wings.

3.3 Components of Mechanism

A 3-D geometric model of the mechanism implemented in the MAV system is developed in AutoCAD. Some snaps of the MAV in CAD are shown in the Fig. 4. This model helps in visualisation of the test device. The design of suitable supports for the mechanism and interference between links are avoided by iteration.

The design methodology for a planar mechanism has been adopted. However, the links cannot lie in a single plane as that would lead to interference. The links have to be selectively staggered in the spatial direction as shown in the Fig. 5. The representation in Fig. 5 with Fig. 3 that shows the kinematic representation of the same design may be compared.

Figure 4. Pictorial view of the proposed mechanism

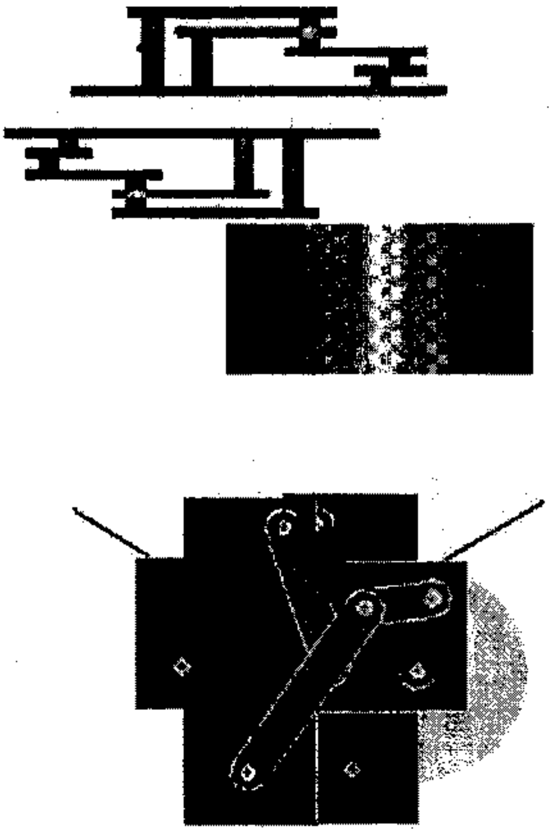

Figure 5. AutoCAD 14 view of the arrangement of the linkages in layers.

3.4 Estimated Lift

An estimate of the lift which would be generated by such a mechanism has been given by Lighthill[2]. The lift per unit width, L, is evaluated in terms of the circulation, Γ, present around each wing and then calculated as the product of the density, p, chord length, c, and the forward velocity, U of the device. For the type of motion presented, the circulation Γ is found to have a value given by $\Gamma = 0.69\ \Omega c^2$, where Ω is the angular velocity of the wing. The lift on the wing can be expressed in terms of lift coefficient, C_L, defined as

$$C_L = L/(0.5\rho\ U^2 c)$$

This leads to

$$C_L = (1.38\ \Omega\ c)/U$$

For the designed apparatus, the angular speed will be about 60 rpm and c would be around 15 cm. This would give a lift coefficient of 1.38 for a forward speed of 1 m/s. This is comparable to the lift on a well-designed airfoil at an angle of attack[5] of about 6-8°.

4. CONCLUSIONS & FUTURE WORK

An approach to design a flying mechanism different from the approaches being followed by researchers around the world[6] has been described. Simple flapping, which is an oscillatory motion of the wings about a fixed axis, does not generate sufficient lift. Although biologists have reported the efficiency of the Weis Fogh model[2], the design using this model has not been attempted so far. The most probable reason for this is that it seems to be a complicated 3-D motion. In the present study, the motion by a single drive through design of the linkages has been achieved.

Development of a mechanism that simulates Weis Fogh model is the first step towards developing an MAV. A robust model of the MAV using this concept is being fabricated to measure the resulting lift. The future work will also involve designing for forward moving, reducing the weight of the device using lighter materials, the holistic design of the MAV, including the structure of the device, the controllers, the gyroscopes for stabilising, and developing small power sources. Also on the agenda will be design improvements to achieve high flight speeds, better stability in air, etc. The overall aim will be to minimise the size and weight, to increase the speed, and to maximise the battery life for this MAV.

ACKNOWLEDGEMENT

The authors wish to acknowledge the Aeronautical Research & Development Board for the grant (Aero/RD-134/100/10/AP/2000-2001/1127) for carrying out this research.

REFERENCES

1. McMichael, J.M. & Francis, M.S. Micro air vehicles-toward a new dimension in flight. Defense Advanced Research Projects Agency (DARPA) and Defense Airborne Reconnaissance Office, USA. http://www.darpa.mil/tto/mav/mav_auvsi.htm
2. Lighthill, M.J. On the Weis Fogh mechanism of lift generation. *J. Fluid Mech.*, 1973, 60(1), pp. 1-17.
3. Batchelor, G.K. An introduction to fluid dynamics. Cambridge University Press, UK, 1993.
4. Ghosh, A. & Mallik, A.K. Theory of mechanism and machines, Ed. 2. Affiliated East West Press Ltd, 1995.
5. Anderson, J.D. Introduction to flight, Ed. 4. McGraw Hill, 2000.
6. Liu, H.; Ellington, C.P., *et al.* A computational fluid dynamic study of hawk moth hovering. *J. Experi. Bio.*, 1998, 201, 461-77.

Contributors

Dr S. Mukherjee obtained his BTech from the Indian Institute of Technology (IIT), Kanpur, in 1985 and his MS and PhD both from the Ohio State University, USA. He started his teaching career at IIT, Kanpur, in 1992. He has been working as Associate Professor at the Dept of Mechanical Engineering at IIT Delhi since 1997. He is a recipient of the *AICTE Career Award for Young Teachers*, and the *INAE Young Investigator Award.*

Dr S. Sanghi is Associate Professor in the Applied Mechanics Dept at IIT Delhi. Having obtained his BE from IIT, Kanpur, he worked with the John Lumley for his MS from the Cornell University. He got his PhD from the Levich Institute of the City College of City University, New York. His research interests include single-phase and multi-phase turbulent flows, CFD and nonlinear dynamics and chaos. He is a recipient of the *Ralph Boliagno Award* for being the most distinguished Teaching Assistant at the Cornell University and the *distinguished Teacher Award* (2002) at IIT Delhi.